Purpose and Scope of Report

The purpose of the report is to document the findings of the study, which include descriptions of the geohydrologic framework, analyses of the chemical and isotopic character of the ground water, and conceptual and mathematical representation of three separate aquifer systems in the study area. This report describes the geohydrology of the upper Ash Creek drainage basin ground-water system and the aquifers within the central Virgin River basin formed by the Navajo Sandstone and the Kayenta Formation. The Navajo Sandstone and the Kayenta Formation are two of the formations that make up the principal regional aquifer of the Colorado Plateau, the Glen Canyon aquifer. For this report they will be referred to individually as the Navajo aquifer and the Kayenta aquifer. Information was compiled and analyzed regarding their lateral and vertical extents, hydraulic properties, ground-water budgets, and directions of ground-water flow.

In addition to the data provided by previous investigations, hydrologic data collected for this study included water level measurements in wells, discharge measurements from pumping wells and springs, discharge measurements in streams, aquifer testing, and the collection of water samples for the analysis of general chemistry, stable and radioactive isotopes, dissolved gases, and chlorofluorocarbons (Wilkowske and others, 1998). Water levels were measured in about 30 wells in the upper Ash Creek drainage basin and in about 80 wells in the Navajo and Kayenta aquifers to determine the configuration of water-level contours (Wilkowske and others, 1998, tables 1 and 2). Most of the municipal well pumpage information was available from the Utah Division of Water Rights and private well owners; however, power consumption and discharge were measured at 14 irrigation wells in the Navajo and Kayenta aquifers southwest of Hurricane and at 8 irrigation wells in the upper Ash Creek drainage basin to estimate annual average rates of ground-water discharge (Wilkowske and others, 1998, table 1). Surface-water discharge was measured at 58 sites in the study area to determine the relative amount of stream loss and gain and the locations where these losses and gains occur (Wilkowske and others, 1998, table 6). Four aquifer tests were conducted at wells that pump water from the Navajo Sandstone and one aquifer test was conducted at a well that pumps water from the igneous rocks in the upper Ash Creek drainage basin.

Field and laboratory analyses were done on ground- and surface-water samples, not to characterize water quality, but to evaluate surface- and ground-water relations and to get a sense of how water enters, moves through, and leaves the ground-water systems of interest. Specific conductance, water temperature, and pH were measured at many of the surface water and ground-water sites inventoried to determine the range and the areal and temporal trends of the values (Wilkowske and others, 1998, tables 3, 4, 5, 6). Water samples for general chemistry were collected at 7 wells, in addition to a compilation of 113 previously reported analyses (Wilkowske and others, 1998, table 4). Thirty-four samples were analyzed for the stable isotopes of oxygen and hydrogen; 25 water samples and 2 rock samples were analyzed for strontium isotopes; and 2 water samples were analyzed for the radioactive isotope of hydrogen (tritium) (Wilkowske and others, 1998, table 5). Water samples from 36 sites were analyzed for chlorofluorocarbons and 6 samples were analyzed for dissolved gases (Wilkowske and others, 1998, table 5).

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GEOHYDROLOGIC FRAMEWORK

The central Virgin River basin study area is located at the transition zone between the Basin and Range and the Colorado Plateau Physiographic Provinces (Fenneman, 1931). This area contains a variety of geologic structures and outcropping formations, many with proven or potential ground-water reserves. Generally northward-dipping sedimentary rock formations of Permian through Tertiary age cover most of the study area and include water-bearing sandstones, siltstones, conglomerates, and limestones (table 1). In addition, the cores of the Pine Valley and Harmony mountain ranges are composed of fractured igneous rocks which can yield from small to large amounts of water.

The Navajo Sandstone and Kayenta Formation provide most of the potable water in the region. Normal faulting along the Hurricane and Gunlock Faults has resulted in offset of most of the outcropping sedimentary formations, including the Navajo Sandstone and the Kayenta Formation, likely resulting in lateral boundaries to the flow of ground water in these formations (pl. 1). Fracturing, commonly observed in the Navajo Sandstone and the Kayenta Formation, can greatly enhance the movement of ground water. In addition, unconsolidated alluvial deposits line the valley bottoms along Ash Creek, the Virgin River, and the Santa Clara River and generally consist of coarse-to-fine-grained, unconsolidated sediments that generally have been developed as a source of irrigation water (pl. 1). Recent Quaternary volcanic eruptions have left a veneer of basalt along large parts of the Ash Creek and Santa Clara River Valleys, as well as on top of the Navajo Sandstone outcrop east of Hurricane and north of St. George (pl. 1). Some of the fractured basalt acts as shallow, highly permeable aquifers, and provides conduits for rapid recharge to underlying formations.

Table 1. Hydrostratigraphic section of selected water-bearing formations within the central Virgin River basin study area, Utah

[Adapted from Hurlow, 1998]

Age	Geologic unit	Abbreviation	Thickness (feet)	Lithologic character	Aquifer
Quaternary	Sediments and basalt	Qs	0-1,200	Boulders, gravel, sand, and silt	Quaternary basin-fill, alluvial-fan, and basalt aquifers
Quaternary—Tertiary	Basalt	QTb	0-550	Fractured, broken basalt	
	Alluvial-fan deposits	QTaf	0-350	Poorly sorted boulder conglomerate	
Tertiary	Undifferentiated igneous and sedimentary deposits	Tsi	0-9,500	Fractured monzonite, volcanic ash-flow tuff, andesite, volcanic breccia, sandstone, conglomerate, and limestone	Pine Valley monzonite aquifer
Cretaceous	Undifferentiated	Ks	3,800-4,000	Sandstone, siltstone, mudstone, and conglomerate	
Jurassic	Carmel Formation	Jc	700	Limestone, shale, and gypsum	
	Navajo Sandstone	Jn	2,000-2,800	Fractured, cross-bedded sandstone	Navajo aquifer
	Kayenta Formation	Jk	800-900	Sandstone, siltstone, and silty mudstone	Kayenta aquifer
	Moenave Formation	Jm	450	Siltstone	
Triassic	Petrified Forest Member of Chinle Formation	Trcp	400	Shale, claystone, and siltstone	
	Shinarump Member of Chinle Formation	Trcs	80-150	Medium-to-course grained sandstone and chert pebble conglomerate	
	Moenkopi	Trm	1,550-2,500	siltstone, mudstone, and shale	
Permian	Undifferentiated	Pu	3,350-3,550	Limestone, shale, sandstone, dolomite	

Upper Ash Creek Drainage Basin

Hurlow (1998) describes 13 different formations of varying lithology represented within the upper Ash Creek drainage basin. Eleven of those formations have been consolidated into three aquifers for this report (table 2). The aquifers were named for use in this report on the basis of the lithologic unit that was deemed of greatest importance to ground-water movement in that formation. The principal aquifers that are thought to form the ground-water system in the upper Ash Creek drainage basin are the Quaternary basin-fill aquifer, the Tertiary alluvial-fan aquifer, and the Tertiary Pine Valley monzonite aquifer. The Quaternary basin-fill aquifer consists of Quaternary sediments, Quaternary basalt, and Quaternary-Tertiary alluvial-fan deposits. The Tertiary alluvial-fan aquifer consists of the upper, middle, and lower members of the Pliocene-Miocene alluvial-fan deposits. The Tertiary Pine Valley monzonite aquifer consists of the Racer Canyon Tuff, the Pine Valley monzonite and latite, the Stoddard Mountain Intrusion, the Quichapa Group, the Claron Formation, and the Iron Springs Formation as shown in Hurlow (1998, p. 42).

Basin-Fill Deposits

Sedimentary deposits included in the Quaternary basin-fill aquifer originated from alluvial and fluvial erosion from surrounding mountains and plateaus. The deposits are interbedded with basalt from a local eruptive center. The deposits contain material that ranges in size from boulders to silt. Thickness of the deposits in the upper Ash Creek drainage basin is generally about 100-500 ft in the western part of the basin near New Harmony, but increases to about 1,000-1,500 ft near the Hurricane Fault.

Alluvial-Fan Deposits

As described in Hurlow (1998), erosion of the volcanic material to the west of the study area is preserved in the upper Ash Creek drainage basin as alluvial-fan and debris-flow deposits. The Tertiary alluvial-fan deposits underlie the Quaternary basin fill in the upper Ash Creek drainage basin. Only a few wells in the area are completed in the alluvial-fan deposits. Maximum thickness for the deposits could be as much as 1,500 ft along the presumed east-west axis of the

Table 2. Hydrostratigraphic section of the upper Ash Creek drainage basin area, Utah

[Adapted from Hurlow, 1998]

Age	Geologic unit		Thickness (feet)	Lithologic character	Aquifer
Quaternary	Quaternary sediments		0-1,500	Boulder gravel, sand, and silt	Basin fill
	Quaternary basalt		0-500	Fractured, broken basalt	
	Alluvial-fan deposits		0-150	Poorly sorted boulder conglomerate	
Tertiary	Alluvial-fan deposits	Upper	0-700	Unconsolidated boulder gravel	Alluvial fan
		Middle	0-450	Siltstone with conglomerate beds	
		Lower	350	Cemented breccia, sandstone, and siltstone	
	Racer Canyon Tuff		1,000		
	Pine Valley monzonite & latite			Fractured monzonite and latite	Pine Valley monzonite
	Stoddard Mountain Intrusion				
	Quichapa Group		1,000	Cemented to partially cemented volcanic ash	
	Claron Formation		700-1,000	Sandstone, limestone, shale, and conglomerate	
Cretaceous	Iron Springs Formation		3,800	Sandstone, shale, and conglomerate	

inferred New Harmony structural basin. Hurlow (1998) indicated that the deposits consist of three members; lower, middle, and upper. The lower and middle members are consolidated to semiconsolidated where they crop out, and are considered to be poorly permeable because of poor sorting, fine grain size, and substantial cementation. The upper member is poorly sorted, but also unconsolidated and coarse grained, and is known to yield water to a few domestic wells on the flanks of the Harmony Mountains.

Pine Valley Monzonite and Other Formations

The igneous and sedimentary formations that underlie and laterally bound the alluvial-fan and basin-fill deposits are designated the Pine Valley monozonite aquifer in this report. Igneous plutonic and volcanic rocks associated with the mid-Miocene Pine Valley Mountain igneous center (Cook, 1957) are exposed south and southeast of New Harmony, including basalt flows, rhyolitic ash-flow tuff, andesite flows, volcanic breccia, sandstone, conglomerate, siltstone, and mudstone (Hurlow, 1998). Other igneous and sedimentary rocks are exposed to the north and west of New Harmony in the Harmony Mountains. These rocks are faulted and folded in the Harmony Mountains and faulted beneath the alluvial-fan deposits under New Harmony. The subsurface geometry is not well known. Hurlow (1998), on the basis of his and previous work on the structure and stratigraphy of the area, put the thickness of the Pine Valley monozonite at about 1,000 ft. Other Tertiary intrusions and volcanics are thought to be about 1,000 ft thick. The Claron Formation is from 700 to 1,000 ft thick. Thus, the transition from the Pine Valley monzonite aquifer to deeper formations probably happens at about 1,000 to 3,000 ft below land surface. The hydrologic nature of this transition is not known.

Navajo Sandstone and Kayenta Formation

The Navajo Sandstone and underlying Kayenta Formation are of Jurassic age and are stratigraphically near the center of a suite of Permian to Quaternary sedimentary formations found within the study area (table 2). In general, the Navajo Sandstone is well sorted, consisting primarily of fine-to-medium sand-size quartz grains (Cordova, 1978, table 1). Petrographic analysis of borehole cuttings indicates that the cementation between sand grains includes varying amounts of calcite, silica, and hematite (J. Wallace, Utah Geological Survey, written commun., 1997). Because the Navajo Sandstone was deposited under eolian conditions, bedding and cross-bedding features are prominent throughout the formation. A detailed lithologic description of the Navajo Sandstone is given by Hurlow (1998). The Navajo Sandstone, where buried by overlying formations, is about 2,400 ft thick; individual measurements include 2,800 ft west of the Gunlock Fault, about 2,300 ft at Harrisburg Junction, and about 2,000 ft at Sandstone Mountain. The lowest 100 to 150 ft of the Navajo Sandstone is defined by Hurlow (1998) as a transition zone containing siltstone and fine-grained sandstone typical of the Kayenta Formation interbedded with cross-bedded sandstone typical of the Navajo Sandstone. The Kayenta Formation consists of laminar beds of sandstone, siltstone, and silty mudstone. Where buried by overlying formations, thickness of the Kayenta Formation ranges from about 380 to 930 ft but is estimated to be about 850 ft through most of the study area (Hugh Hurlow, Utah Geological Survey, oral commun., 1998). The vertical thickness of the Navajo Sandstone and Kayenta Formation generally decreases to the south are due to erosion (fig. 4).

Tectonic forces have folded and faulted the Navajo Sandstone and Kayenta Formation. The major folds within the study area (fig. 5), from east to west, are (1) the Hurricane Bench syncline, (2) the Virgin anticline, (3) the St. George syncline, and (4) the Gunlock (or Shivwits) syncline (Cordova, 1978, p. 11; Hurlow, 1998). Because of a generally northward dip, the Navajo Sandstone and Kayenta Formation become deeply buried toward the northern boundary of the study area. The ARCO Three Peaks #1 oil exploration drill hole 10 miles northwest of Cedar City (about 50 mi northeast of St. George) reached the top of the Navajo Sandstone at a depth of 6,286 ft beneath land surface, or about 900 ft below sea level (Van Kooten, 1988). Tilting associated with the Hurricane Fault causes the Navajo Sandstone and Kayenta Formation in the northeast part of the study area to dip steeply; the top of the Navajo Sandstone is estimated to be buried as deep as 2,000 ft below sea level (Hurlow, 1998, pl. 5B). The Hurricane Fault completely offsets the Navajo Sandstone and Kayenta Formation along its entire trace. The Gunlock Fault offsets the Navajo Sandstone and the Kayenta Formation to some point north of Gunlock Reservoir (Hintze and Hammond, 1994). West of the Gunlock fault, the Navajo Sandstone and Kayenta Formation dip northeast more steeply than the gently dipping synclines east of the fault (fig. 5; Hurlow, 1998, pl. 5b). Other faults that partly offset the Navajo Sand-

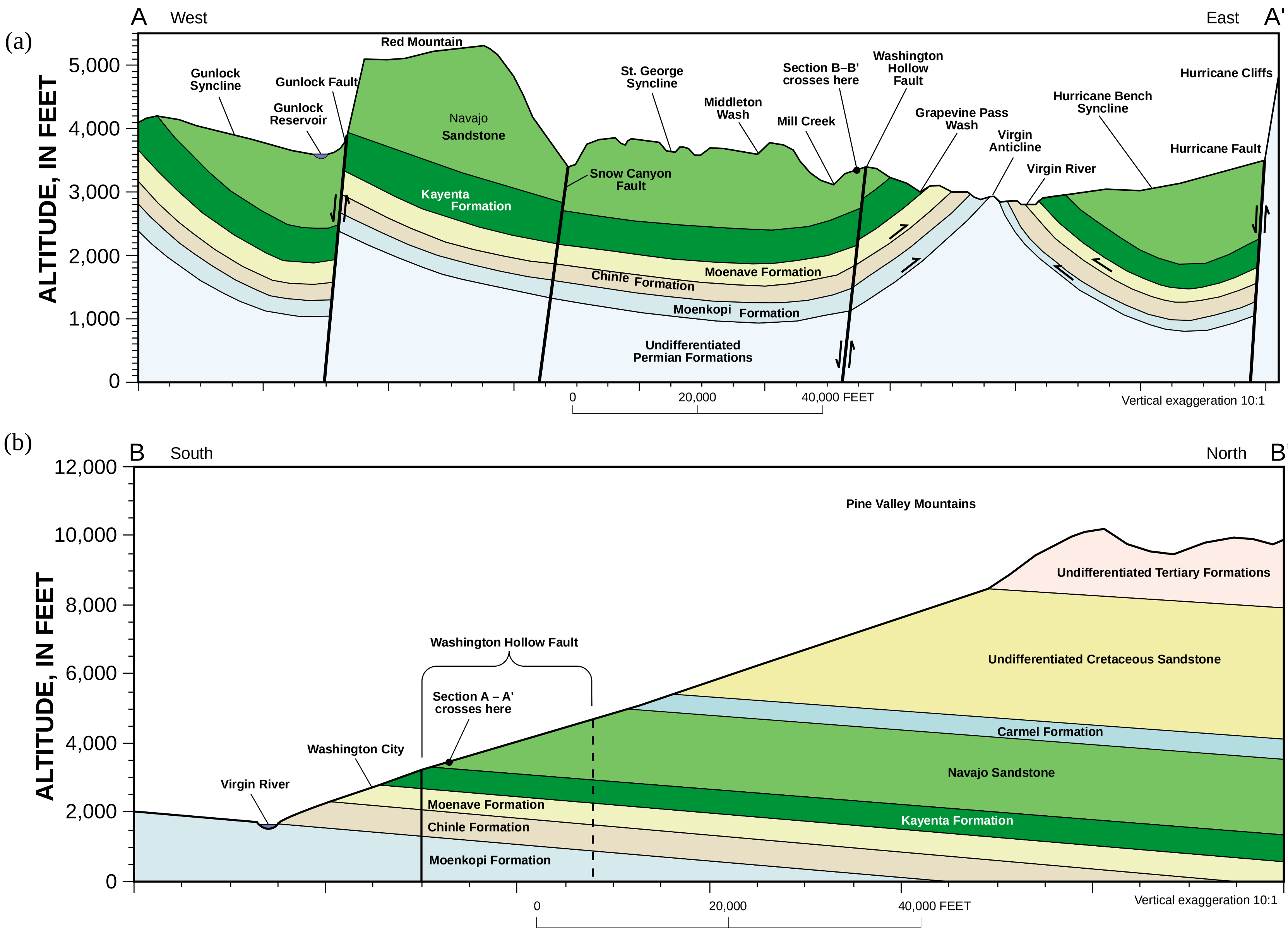

Figure 4. Generalized geologic cross sections of the Navajo Sandstone and surrounding formations within the central Virgin River basin study area, Utah. Location of cross section (a) shown by line A-A' on plate 1. Location of cross section (b) shown by line B-B' on plate 1.

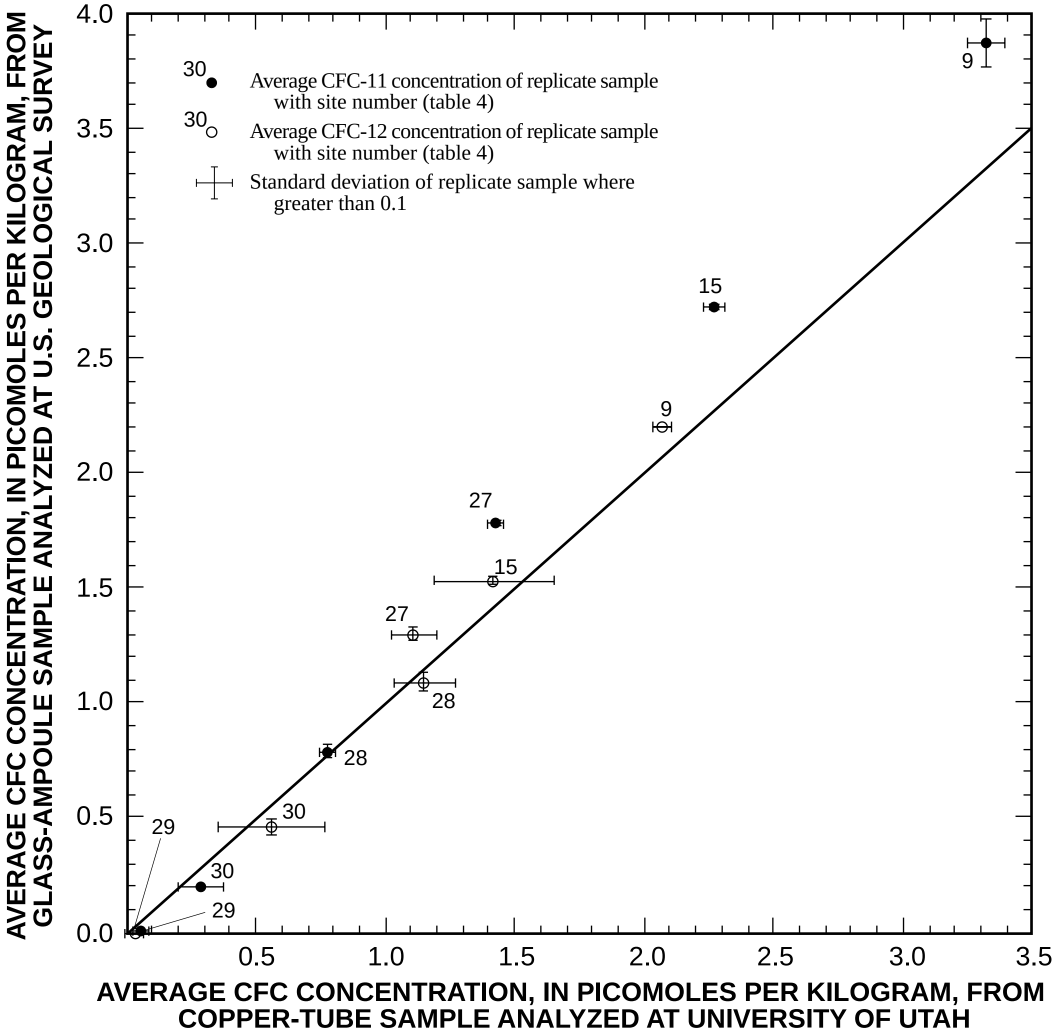

Figure 5. Average CFC-11 and CFC-12 concentration in replicate samples collected with the glass-ampoule method and analyzed at the U.S. Geological Survey versus samples collected with the copper-tube method and analyzed at the University of Utah.

stone and Kayenta Formation within the study area include the Washington Hollow Fault north of Washington and an unnamed series of faults between Anderson Junction and Toquerville (pl. 1). These faults, along with other numerous faults whose actual offset is difficult to measure, such as the Snow Canyon Fault and the Washington Hollow Fault, likely act as barriers to ground-water flow perpendicular to the fault plane, yet may act as conduits parallel to the fault plane. Low transverse permeability is expected perpendicular to the fault because of poorly-sorted breccia and finer clay-rich materials generally found along the plane of the fault, such as cataclasite, gouge, and secondary calcite cementation (Hurlow, 1998, p. 20).

Extensive joints and joint zones are found in the Navajo Sandstone and Kayenta Formation outcrops. Unlike faults, there was no movement along the fracture plane of joints during their formation, so they do not contain low-permeability gouge or breccia zones and thus allow ground water to move perpendicular to the joint plane. Similar to fault zones, joints probably act as conduits parallel to the joint plane. Joints within the study area are essentially vertical, dipping at angles generally greater than 70 degrees. Surface fracture mapping indicates that individual joints have surface traces of as much as 600 ft in length, and interconnected joint networks may extend thousands of feet laterally (Hurlow, 1998).

Aerial photographs published by Cordova (1978) generally show a prominent north-south fracture trend in the central part of the study area. However, a more detailed fracture analysis of the Navajo Sandstone in the study area based on both aerial photographs and outcrop data shows large variation in both the orientation of prominent fractures and the fracture density (Hurlow, 1998, pl. 6). In general, the aerial photograph data and the outcrop data indicate prominent fracturing in the north-south orientation between Anderson Junction and the Gunlock Fault (Hurlow, 1998, p. 27). However, some rose-diagram plots of data from Anderson Junction, Sandstone Mountain, Washington Hollow, and the Red Mountains show an additional east-west to northwest trending set of fractures (Hurlow, 1998, pl. 6). Rose diagrams from aerial photographs depicting joint frequency weighted by fracture length emphasize the orientation of the longer joints and joint zones. Rose diagrams from outcrop data are not weighted toward the longer joints and thus may be less meaningful with regard to the regional movement of ground water. In addition, the outcrop data contain an inherent sampling bias because more resistant, less fractured outcrop locations provide the best surfaces for conducting the surveys. This is likely a problem along the Santa Clara River west of the Gunlock Fault, where outcrop data show the main fracture orientation to be east-northeast, whereas aerial photographs (Cordova, 1978) and field observations indicate predominant north-south trending fractures. The recent study by Hurlow (1998) suggests that no correlation exists between outcrop fracture density and aerial-photograph-determined fracture density. Generalized conclusions based on aerial photograph data indicate that fracture density generally is high at Snow Canyon, Anderson Junction, Sandstone Mountain, and near the Gunlock Fault zone; contrarily, fracture density from aerial photographs is relatively low near Mill Creek and Sand Mountain (Hurlow, 1998).

About 25 percent of the outcrop surface of the Navajo Sandstone and Kayenta Formation is covered by sand dunes, alluvial deposits, and basalt flows (pl. 1). Sand dunes and alluvial deposits generally are less than 150 ft thick (Hurlow, 1998, pl. 4). However, two areas of the Navajo Sandstone outcrop are overlain by thicker wedges of alluvial deposits at Anderson Junction (more than 350 ft thick) and south of Hurricane near Gould Wash and Frog Hollow Wash (pl. 1). The thickness of basalt covering the Navajo Sandstone outcrop generally is less than 100 ft (Hugh Hurlow, Utah Geological Survey, oral commun., 1998).

HYDROCHEMICAL CHARACTERISTICS

Knowledge of the role of ground water in the hydrochemical framework of a ground-water system is as important as knowledge of how aquifers fit into the geologic framework of an area. To investigate ground-water direction and rate of movement within the Navajo and Kayenta aquifers and the Ash Creek drainage basin, chemical and isotopic data from water samples were collected or compiled from previous investigations (Wilkowske and others, 1998, tables 4 and 5). CFC, dissolved gas, general chemistry, and stable isotope data were used to evaluate potential sources of recharge to the aquifers and average residence times within the aquifers, both of which aid in determining possible ground-water flow directions.

Methods and Limitations

Chlorofluorocarbon Collection Methods

Concentrations of chlorofluorocarbons (CFCs) in the modern atmosphere are greater than in older ground water that entered the water table in the past, so care must be taken to avoid sample contamination via contact with modern air. Two methods have been developed to collect water samples for CFC analysis that prevent atmospheric contamination—the copper-tube method and the glass-ampoule method.

The copper-tube collection method requires that CFC samples be collected in sealed 3/8-in.-diameter copper tubes approximately 30 in. long (about a 30-mL sample). Prior to sampling, the tubes were annealed in an argon atmosphere at 600 ˚C, which cleaned the tubes and made them easier to seal. Rubber and plastic gaskets can absorb CFCs and be a source of contamination; therefore, the tubes were connected directly to well heads using all metal connections. For the collection of spring and surface-water samples, the copper tubes were placed directly in a flowing spring or stream. A 2-ft piece of Tygon tubing with a plastic pinch valve was connected to the downstream end of the tube to prevent any back diffusion of atmospheric CFCs into the sampler. The tubes were then flushed with at least 10 sample volumes of ambient water. While water was flowing through the sampler, the copper tube was crimped off using a hand-held crimping tool. This seal holds best under a vacuum, so prior to sampling, a 1-to 2-in. section of the copper tube was flattened using pliers to reduce the volume of the sampler. After crimping the